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YELLOW HYPERGIANTS SHOW LONG SECONDARY PERIODS?

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ABSTRACT

There is observational evidence that intermittent long secondary periods of ∼1000 days are present in the well-observed yellow hypergiants ρ Cas and HR 8752. The long secondary period is interpreted here as the turnover time of giant convection cells in the convective envelope, as has been already suggested in the case of red giants and supergiants of high luminosity. The observed secondary periods and surface radial velocities of ρ Cas and HR 8752 agree with the theoretical predictions, within the expected errors. These results support a theoretical interpretation that now covers the entire initial mass range from 1 to 50 $M_\odot$ for luminous cool stars.

Key words: convection – stars: interiors – stars: oscillations – stars: variables: general – supergiants

1. INTRODUCTION

Yellow hypergiants constitute a small class of very luminous supergiants that exhibit unusually turbulent photospheres and high rates of mass loss, including occasional great outbursts or eruptions that form a dense, optically thick, cool wind that temporarily obscures the photosphere (de Jager 1998; Oudmaijer et al. 2009). These stars are thought to have evolved from an immediately preceding red-supergiant state (Stothers 1975). The observational evidence for evolution from the red, however, is strong only in the case of IRC+10420, which is now known to be a bona fide yellow hypergiant (Jones et al. 1993; Oudmaijer et al. 1996). This star has displayed decades-long increases of both visual brightness (Gottlieb & Liller 1978) and effective temperature (Klochkova et al. 2002), although these increases have ceased in recent decades. The visual brightening would be an effect of bolometric correction or else of thinning of the circumstellar dust shell (Humphreys et al. 2002). This massive dust shell is believed to have been ejected either ∼200 yr ago (Oudmaijer et al. 1996) or, more likely, 60–90 yr ago (Blöcker et al. 1999; Tiffany et al. 2010). Similar rates of long-term increase in visual brightness have been measured for the stars ρ Cas (de Jager & Nieuwenhuijzen 1997), HR 8752 (Arellano Ferro 1985; Zsoldos 1986), and Var A in M33 (Humphreys et al. 1987) if we ignore the temporary dimming caused by the occasional outbursts.

No yellow hypergiant is certain to be hotter than ∼8500 K, so that the luminous region of the Hertzsprung–Russell diagram (log $(L/L_\odot) > 5.4$) with effective temperatures between 8500 and 12,000 K appears to be nearly devoid of stars. This region has been called the Yellow Evolutionary Void by de Jager & Nieuwenhuijzen (1997). Although mass eruptions can be very violent, a yellow hypergiant appears to remain persistently confined to the occupied region, even if this region's hot boundary is not very well defined owing to the difficulty of determining the true effective temperature of a yellow hypergiant at any time.

Theoretical evolutionary tracks reproduce this behavior to a satisfactory extent. When the mass of a very luminous red supergiant has declined sufficiently as a consequence of stellar wind mass loss, the star develops dynamical instability that is induced by high radiation pressure in combination with the partial ionization of hydrogen and helium within the diminished outer layers (Stothers & Chin 1993). Assuming that dynamical instability leads to sporadic outbursts of mass loss as hydrodynamical calculations suggest (Tuchman et al. 1978; Stothers 1999), it is found that a suddenly imposed mass-loss rate of $10^{-2}\,M_\odot$ yr^{-1} or higher triggers in the evolutionary models a transient blue loop which typically extends to ∼7000 K, although the maximum effective temperature achieved depends on the assumed mass-loss rate (Stothers & Chin 2001). The exact cause of the blue loop, though still uncertain, must be related to the physical condition that these stars are secularly (thermally) unstable, and a large mass-loss perturbation can remove enough thermal energy from the upper part of the envelope to cause a contraction that resupplies the lost energy. A larger perturbation results in a more prolonged contraction, although the rate of contraction (in accordance with Kelvin–Helmholtz theory) remains about the same. This prolongation yields in time a longer blue loop. Sufficient recovery of thermal balance then allows the star to re-expand back into the red-supergiant configuration.

The blue loop evolves on a secular timescale of decades, during which time additional mass outbursts may occur (maintaining the blue loop) since the star remains dynamically unstable. But the star cannot enter or cross the Yellow Void unless its hydrogen envelope becomes extremely thin. Crossing the Yellow Void in either direction, including the immediate post-main-sequence crossing, is very rapid (timescale of hundreds of years). It is interesting that the observed outburst from the yellow hypergiant ρ Cas in 2000 amounted to $5 \times 10^{-2}\,M_\odot$ yr^{-1} (Lobel et al. 2003), which kept the star yellow and is consistent with our theoretical predictions.

In addition to its dynamical and secular instabilities, a yellow hypergiant is subject to several other sources of instability. Its atmosphere becomes gravitationally unbound (or nearly so) due to the effects of radiation, turbulence, and stellar wind if the effective temperature rises above 8000 K, which may help to explain the existence of the Yellow Void (Nieuwenhuijzen & de Jager 1995; de Jager et al. 2001). Another type of instability in these stars is pulsational, since at least some of the yellow hypergiants exhibit quasiperiodic cycles of low-amplitude light and radial-velocity variations with a characteristic timescale of ∼1 yr (de Jager 1998). It is still unclear what these cycles represent: multiple or simply irregular radial pulsation modes, or possibly nonradial (gravity) pulsation modes.

Possibly related to these hypergiants are the most luminous of the ordinary red supergiants, although their one-year cycles are somewhat less irregular. The low-amplitude variations in these

* Deceased.

Table 1
Periods of ρ Cas

P_1 (days)	P_2 (days)	Reference
365	1100	1
200–450	...	2
300–340	...	3
400	...	4
275	...	5
483	...	6
520	...	7
299	...	8
480	...	9
380–650	820	10

References. (1) Hassenstein 1934; (2) Beardsley 1961; (3) Fernie et al. 1972; (4) Percy & Welch 1981; (5) Percy et al. 1985; (6) Arellano Ferro 1985; (7) Sheffer & Lambert 1986; (8) Zsoldos & Percy 1991; (9) Gesicki 1992; (10) Percy et al. 2000.

stars are probably due to radial pulsation, although de Jager (1993) has suggested nonradial gravity modes. What interests us here are the long secondary periods that are also observed, with lengths of several years (Stothers & Leung 1971; Kiss et al. 2006). Considerable evidence now exists that these slow periods represent the turnover time of giant convection cells in a stellar envelope that is both very deep and strongly convective (Stothers 2010). Although for initial stellar masses below $\sim 30\,M_\odot$ such envelopes are found only in red giants and supergiants, their presence does extend into the region of yellow hypergiants at higher stellar masses (see Figure 5 of Maeder 1980). The question we ask here is whether yellow hypergiants likewise show long secondary periods. Observational records having a length and continuity sufficient to answer this question exist only for ρ Cas and HR 8752, and so it is these two stars that we examine here, both observationally (using published data) and theoretically.

2. OBSERVATIONAL DATA

2.1. ρ Cas

The yellow hypergiant ρ Cas shows a spectral type F8 Ia$^+$, which develops into a later type during the phases of shell ejection when a pseudo-photosphere develops. Recent outbursts, detected both photometrically and spectroscopically, have taken place in 1946, 1986, and 2000 (Lobel et al. 2003 and references therein). Variability of the star's light on a much shorter timescale also exists, showing an irregular periodicity of 200–600 days (Table 1).

The key question here is whether there is a possibility of the existence of an additional, long secondary period. Using visual observations for the time interval 1904–1934, Hassenstein (1934) found, in addition to a period of $\sim$365 days, a much longer period of 1100 days. This slow period was not confirmed until Percy et al. (2000) found a prominent period of 820 days in photometric data for 1985–1999. Shorter periods of about a year were also present in their data, but not as conspicuously as in older 1963–1989 data (Zsoldos & Percy 1991). All of the observed cycles (of whatever length) are irregular and of fairly low amplitude (typically 0.2 mag visual). The corresponding radial-velocity amplitudes are $\sim 20\,\mathrm{km\,s^{-1}}$ (Arellano Ferro 1985; Sheffer & Lambert 1986; Lobel et al. 1994, 1998).

Table 2
Periods of HR 8752

P_1 (days)	P_2 (days)	Reference
365	...	1
...	1000	2
387	...	3
365	...	4
315–421	...	5
409	...	6
200–400	1200	7
300[a]	...	8

Notes. [a] 190 or 250 days, according to van Genderen, in Nieuwenhuijzen & de Jager (2000).

References. (1) Percy & Welch 1981; (2) Lambert et al. 1981; (3) Arellano Ferro 1985; (4) Zsoldos 1986; (5) Sheffer & Lambert 1987; (6) Halbedel 1991; (7) Percy & Zsoldos 1992; (8) Nieuwenhuijzen & de Jager 2000.

For the equilibrium parameters of ρ Cas, de Jager (1998) gives $\log(L/L_\odot) = 5.70$, and Israelian et al. (1999) give $\log T_e = 3.86$. These values yield a radius of 450 $R_\odot$. Assuming that ρ Cas has recently evolved out of the red-supergiant region, we have found theoretically that it is necessary for most of the hydrogen envelope to have been lost. This may happen either very quickly or very slowly. In view of the observed paucity of red supergiants with such high luminosities, we assume that the mass-loss rate in the red region must in fact be quite high. Regardless of this uncertainty about the timing, however, the star's mass upon exiting the red region is securely determined, being little more than the mass of the helium core plus a fringe of hydrogen on top. According to our stellar evolutionary models (Stothers & Chin 1996), the mass of ρ Cas should be $\sim 17\,M_\odot$ based on its luminosity. Its initial main-sequence mass must have been close to $45\,M_\odot$, although the occurrence of fast rotation would reduce this estimate somewhat (Meynet & Maeder 2005).

2.2. HR 8752

HR 8572 (V509 Cas) displays a spectral type of G5 Ia$^+$ during its phases of quiescence. This star is sometimes regarded as a twin of ρ Cas, although its outbursts occur more frequently (de Jager & Nieuwenhuijzen 1997 and references therein). Furthermore, its primary period, which probably lies in the range of 300–400 days (Table 2), may be more regular than in ρ Cas. From radial-velocity measurements, Lambert et al. (1981) derived a long secondary period of $\sim$1000 days with an amplitude of $25\,\mathrm{km\,s^{-1}}$, although later observations seemed to show only the primary period with an amplitude of $3\,\mathrm{km\,s^{-1}}$ (Sheffer & Lambert 1987). This apparent shift in the relative visibility of the two periods is reminiscent of the behavior of ρ Cas. Although Percy & Zsoldos (1992) found several photometric periods within the range of 200–400 days, they did not comment on a prominent spectral peak occurring around a period of 1200 days, which would agree with the period of Lambert et al. (1981).

The equilibrium parameters for HR 8752 are listed by de Jager (1998), who gives $\log(L/L_\odot) = 5.60$, and by Israelian et al. (1999) and by C. de Jager (2011, private communication), who give $\log T_e = 3.90$. These values imply a radius of 340 $R_\odot$. Although a smaller luminosity for HR 8752 has recently been proposed (C. de Jager 2011, private communication), the measurement uncertainty is very large and encompasses the older value, which is closer to the luminosity of this star's "twin." The adopted luminosity corresponds theoretically to a present stellar mass of $14\,M_\odot$ (Stothers & Chin 1996). Using measurements of effective surface gravity with the help of stellar atmosphere models, Nieuwenhuijzen & de Jager (2000) inferred a mass of 18.8 (+14.7, −8.2) $M_\odot$, which, despite the large uncertainty, agrees with the theoretical evolutionary value. The initial main-sequence mass would have been $\sim 40\,M_\odot$, or somewhat lower if the star is a fast rotator. From spectroscopic observations de Jager & Vermue (1979) showed that the turbulent elements in the photosphere appear to be huge convection cells, presumably of the type being generated in the interior.

3. THEORY OF GIANT CONVECTION CELLS

The theory of giant convection cells adopted here has already been presented elsewhere (Stothers & Leung 1971; Stothers 2010). Briefly, the cell occupies the whole depth of the envelope convection zone, and the material moves upward and downward at a mean velocity, v, whose inverse, upon integration over the radial extent of the convection zone, gives the convective mixing time:

$$\tau_{\rm mix} = I\left(2M/4\pi\sigma T_{\rm e}^4\alpha\right)^{1/3}.$$

Thus, the full turnover time of the cell is just $2\tau_{\rm mix}$. In this simple expression, M is the stellar mass, $T_{\rm e}$ is the effective temperature, α is the ratio of convective mixing length to pressure scale height, and I is a constant of the order of unity. For yellow hypergiants I can be evaluated analytically, since the density within essentially the entire region that determines the value of $\tau_{\rm mix}$ is nearly constant, and since the adiabatic exponents, Γ, are all very close to 4/3 (see Figure 2 of Stothers & Chin 1993). In this case, $I = 1.25$. We also adopt $\alpha = 1.3$, the same value as the one that has been fitted to the observed effective temperatures of the most luminous red supergiants (Stothers & Chin 1997).

Throughout the convection zone—except near the radiative boundaries at the top and bottom—the mean convective velocity v is roughly a constant (Stothers 2010 and references therein). If the upper radiative boundary is situated high enough in the atmosphere, as is the case for red supergiants, v will be close to the measured photospheric velocity (the direction of motion depending on the phase of the overturning cells). Otherwise, the interior and photospheric velocities will be essentially disconnected. When the number of rising and falling convection cells is very small, their effects will not entirely cancel owing to a likely preponderance at any given time of one type over the other. Thus, for a while, upwelling cells will dominate, followed by the downwelling portion of their cycles. This will observationally resemble a coherent radial pulsation without the large radial amplitude of motion.

4. DISCUSSION

Two pieces of evidence suggest that long secondary periods do exist in yellow hypergiants. First, at least ρ Cas and HR 8752 show long-term quasiperiodic variations in light and radial velocity according to a number of observational studies. These semiregular periods are ∼1000 days in length. Second, if they are explained as the turnover time of giant convection cells in the envelope, the theoretically predicted periods are ∼800 days (Table 3), essentially the same as the observed periods within the expected errors. Since the theory of giant convection cell turnover also accounts very well for the long secondary periods seen in luminous red giants and supergiants, it supports the same causal identification that we have made for these redder stars. Unlike the coolest stars, however, the long secondary periods in the yellow hypergiants are not always readily visible, which is perhaps not surprising since envelope convection in general is stronger at lower effective temperatures.

Table 3
Observed and Predicted Surface Velocities and Long Secondary Periods

Star Name	$T_{\rm e}$ (K)	$M/M_\odot$	$R/R_\odot$	P_2 (days)	$2R/P_2$ (km s^{-1})	ΔV_2 (km s^{-1})	α	$2\tau_{\rm mix}$ (days)
ρ Cas	7300	17	450	900	8	20	1.3	850
HR 8752	7900	14	340	1100	5	25	1.3	720

The predicted surface velocities are assumed in our model to be approximately equal to the mean upward or downward convective velocities existing throughout the envelope convection zone. If so, they should be given by $v \approx 2R/P_2$, where R is the total radius of the convection zone (essentially the stellar radius) and P_2 is the observed long secondary period, interpreted as the giant convection cell turnover time. The predicted surface velocities are then 5–8 km s^{-1} (Table 3). Table 3 also lists the observed radial-velocity amplitudes, $\Delta V_2 \approx 20$ km s^{-1}. To compare them with v, they must first be halved to obtain the relevant semi-amplitude, and then multiplied by a factor p that converts the observed radial velocity to an astrocentric radial velocity by correcting for projection and limb-darkening effects. Although yellow hypergiants lie on an extension of the Cepheid instability strip on the Hertzsprung–Russell diagram, it is by no means certain that the traditional value of $p = 1.4$ (Getting 1934) that has held up in many studies over the years for radially pulsating Cepheids would apply to giant cell motions. We assume that it does, at least approximately, and so we find an astrocentric surface velocity of ∼14 km s^{-1}. In view of the theoretical uncertainties of our simple analytical model, this seems to agree satisfactorily with the expected mean convective velocities in the envelope convection zone.

It might be expected that the strong convective motions at the stellar surface, as well as the massive outbursts, would produce easily observable circumstellar ejecta. This is, surprisingly, not the case for ρ Cas and HR 8752, which show no circumstellar nebulosity, although IRC+10420 does (Schuster et al. 2006; Tiffany et al. 2010). On the other hand, IRC+10420 is a more luminous object, whose surface activity may well be greater.

In the evolutionary scenario presented in this paper, the yellow hypergiants are dynamically unstable objects that repeatedly eject matter in outbursts. When these outbursts are massive and frequent enough, a yellow hypergiant in its underlying evolutionary movement continually pushes toward the Yellow Void. In this situation apart from an occasional mask that is temporarily created by a cool pseudo-photosphere, the effective temperature of the star continues to increase after a massive outburst. Eventually, if no further large outbursts occur, the star will return to the red-supergiant state until another large outburst takes place. The three giant outbursts of ρ Cas during the past century have probably kept this star close to the Yellow Void for most of the time so that its effective temperature will have most likely remained close to 8000–7300 K, as also is observationally suspected (Israelian et al. 1999). On the other hand, HR 8752 has for long experienced only small upward effective temperature excursions, except for a moderate one in 1973 and a very recent, larger one. These variations are superimposed on a slow secular increase of the star's apparent effective temperature over the past 100 years (Nieuwenhuijzen & de Jager 2000; C. de Jager

2011, private communication). This is in agreement with the decadal and century-long timescales theoretically predicted for such excursions if we have rightly considered the observed temperatures as referring to the underlying star after the ejected cloud has become sufficiently optically thin (Stothers & Chin 2001). During the particular time interval that Percy & Zsoldos (1992) analyzed HR 8752 for possible periodicities, the star's average effective temperature was closer to ∼5500 K than to its present 7900 K. Therefore, the theoretically predicted values for HR 8752 in Table 3 should probably be revised to $2R/P_2 = 10\,\mathrm{km\,s^{-1}}$ and $2\tau_{\rm mix} = 1100$ days, with $R/R_\odot = 700$. These revised values show even better agreement with observations.

A plausible and consistent interpretation of the long secondary periods in luminous cool giants and supergiants now exists. The theory covers the mass range from the smallest observed masses up to the largest ones. To verify the theory, accurate observations of more stars are needed, and detailed numerical simulations of the envelope convection zones for cool giants and supergiants, of the kind undertaken recently by Chiavassa et al. (2010) and Arnett & Meakin (2011), will be essential to check the predictions of the present simple analytical model.

It is a pleasure to thank Cornelis de Jager and Hans Nieuwenhuijzen for providing recent information about HR 8752, and the referee, Roberta Humphreys, for many useful suggestions to improve the paper.

Editorial note. We regret to announce the death of the author, Dr. Richard Stothers, on 2011 June 28. The referee, Dr. Roberta Humphreys, had submitted the following edited report that Dr. Stothers did not consider: "Concerning the star Var A, reference should be made to Hubble, E., & Sandage, A. 1953, ApJ, 118, 353. Var A did indeed gradually brighten from 1920 to 1950, but since its high mass loss episode, it has remained faint. A 50 year minimum is hardly temporary (see Humphreys, R. M., Jones, T. J., Polomski, E., et al. 2006, AJ, 131, 2105). The spectrum has recovered but the star is still visually faint."

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